

# PRELIMINARY DESIGN OF A FHR TEST REACTOR CORE

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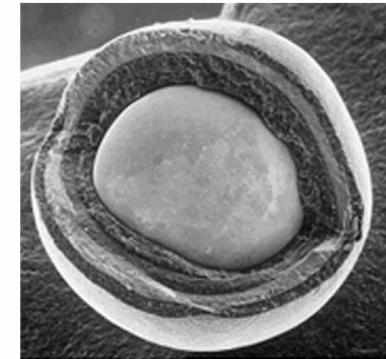
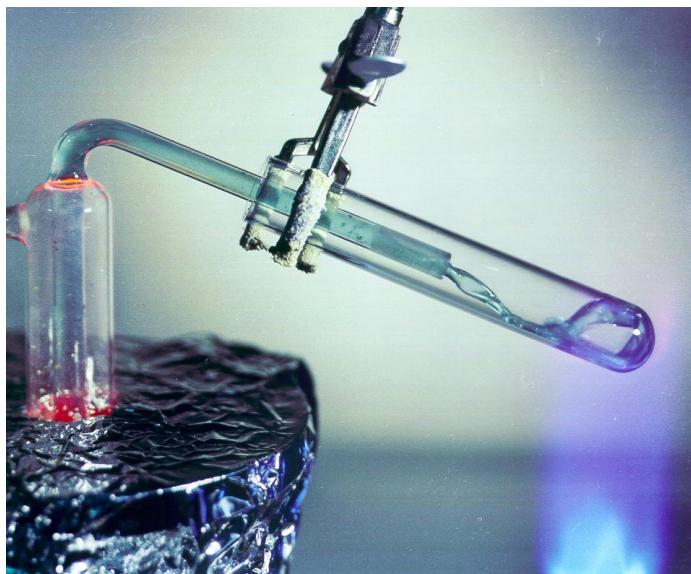
# Outline

- Introduction to the Fluoride Salt Cooled High Temperatures Reactor (FHR) and FHR Test Reactor (FHTR)
- FHTR Design Goals
- Design and evolution of a FHTR
- Conclusions from UCB Design Studies



# FHRs: Fluoride Salt-Cooled High Temperature Reactors

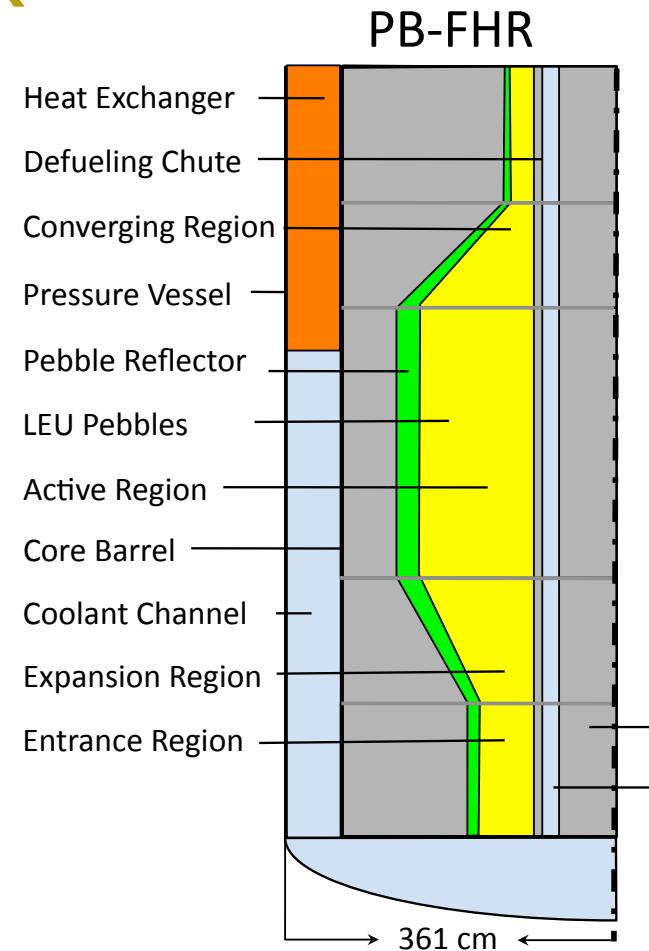
- Fluoride salt coolant
- Flexible TRISO fuel design
- Robust fuel performance
- Enhanced safety features



- Low pressure operation
- High power density
- High energy conversion efficiency
- Low peak-to-average coolant temperature
- Low capital cost

# UC Berkeley: The PB-FHR

- 900 MWth
- 19.9% enriched uranium
- Flibe coolant
- Pebble Fuel
  - Buoyant pebbles
  - Upward pebble circulation in the core
- Potential pebble blanket
- Upward coolant flow



# Purpose of the FHTR

- Experience in operation and licensing pf a FHR-type plant
- Develop knowhow and reveal limitations beyond capabilities of separate effects test facilities
- Generate validation data for computational modeling
- Generate data to assist in licensing commercial PB-FHRs



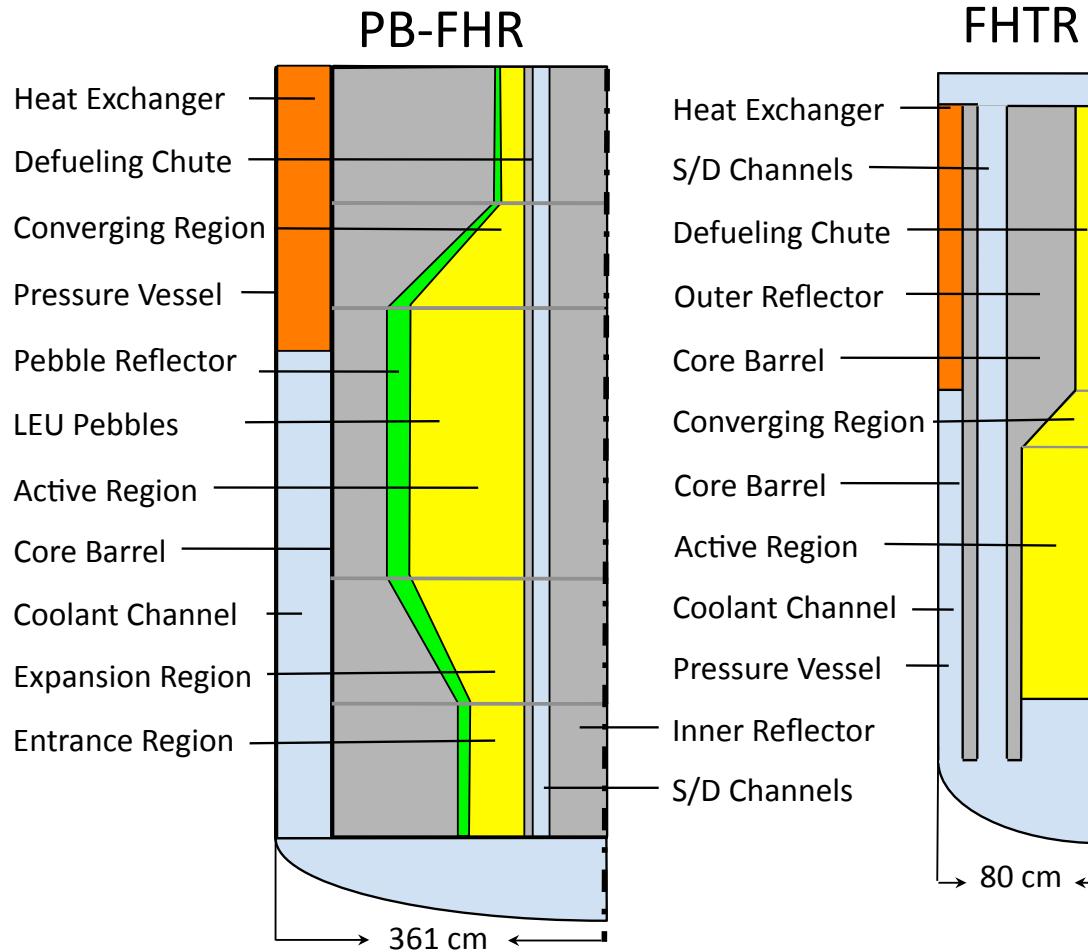
# Test Reactor: Constraints and Objectives

- Safety Constraints
  - Negative coolant and fuel reactivity coefficients
  - Sufficient cold shutdown margin
  - Diverse reactivity control systems
- Design Constraints
  - Availability of flibe → small active region
  - Pebble fuel
  - Matching neutron energy spectrum of commercial PB-FHR
  - Using prototypical materials and fuel
  - Operating at prototypical temperatures and power densities

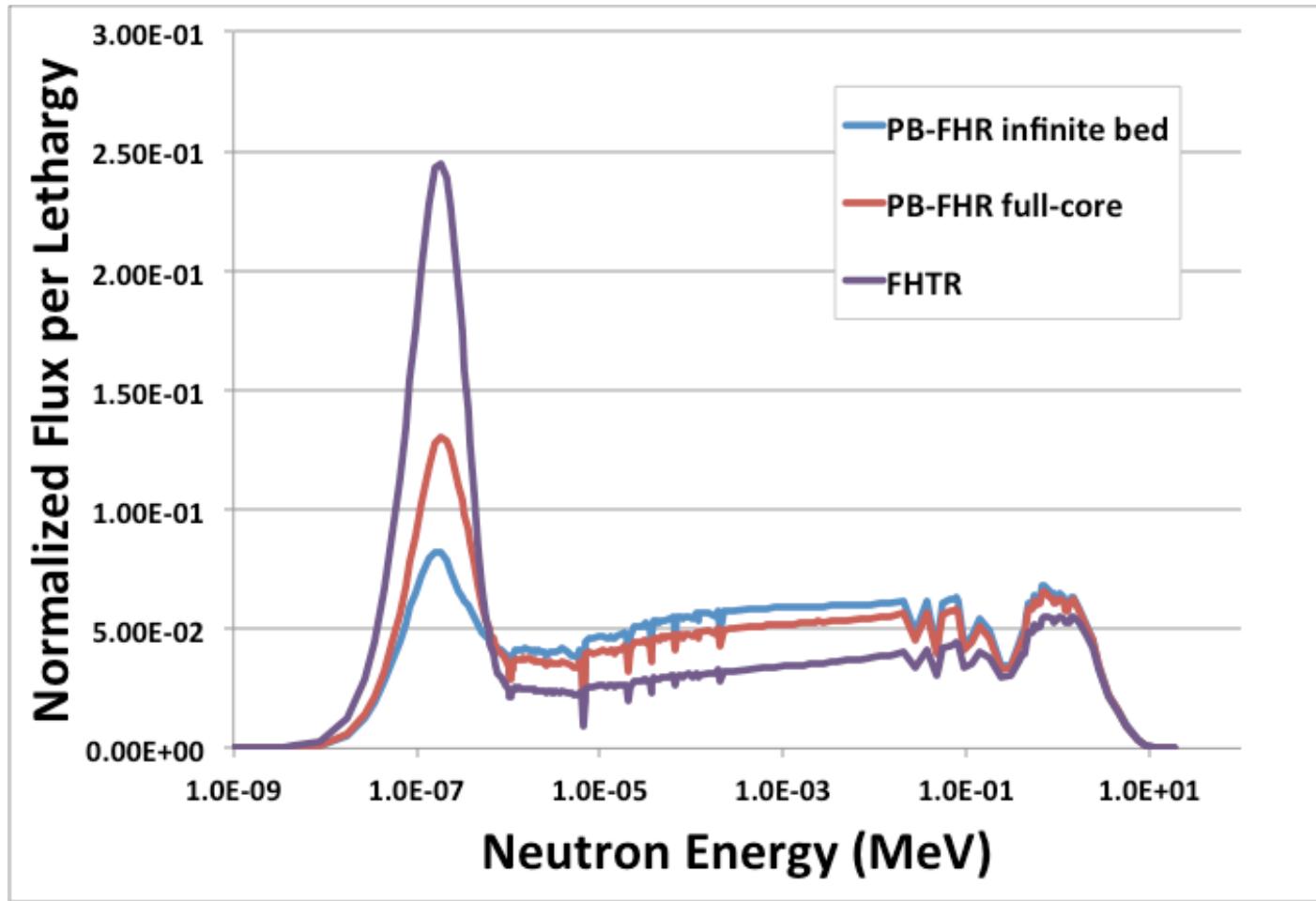
Ideally identical to PB-FHR, but smaller



# Design Comparison: PB-FHR and FHTR



# FHTR with PB-FHR Fuel (C/HM = 300)



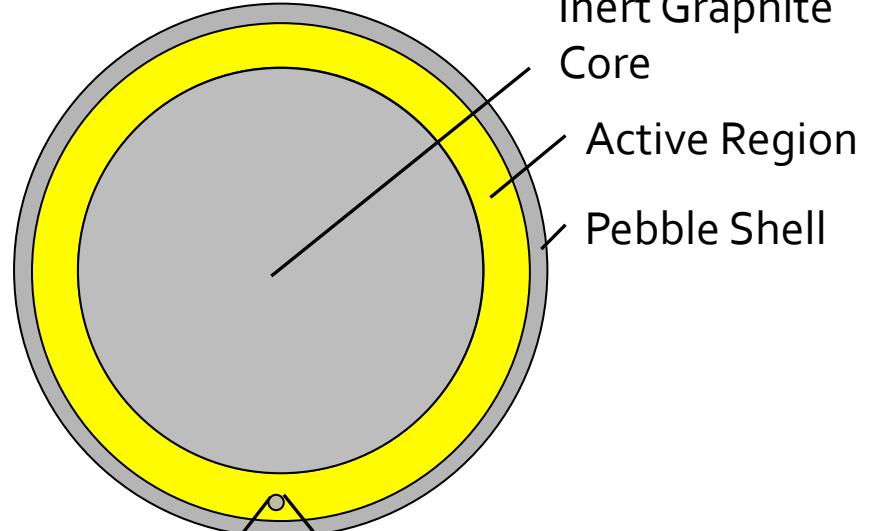
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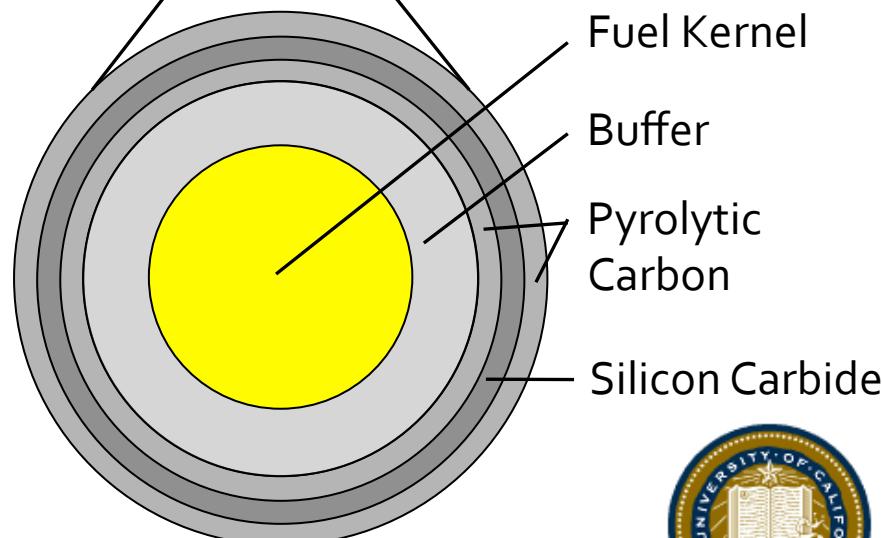
# Fuel Design

Pebble Parameter	300 C/HM	200 C/HM
Pebble Diameter (cm)	3.0	3.0
Thickness of Active Region (mm)	2.57	2.49
Insert Pebble Core Radius (cm)	1.243	1.251
Fuel Particles per Pebble	9990	4730
Density of Inner Core (g/cc)	1.594	1.519
Fuel Particle Diameter (um)	810	810
Fuel Particle Packing Fraction	40%	40%
Power Per Particle (mW)	47	81
Enrichment (wt% $^{235}\text{U}$ / $^{238}\text{U}$ )	19.9%	19.9%

Pebble Scale



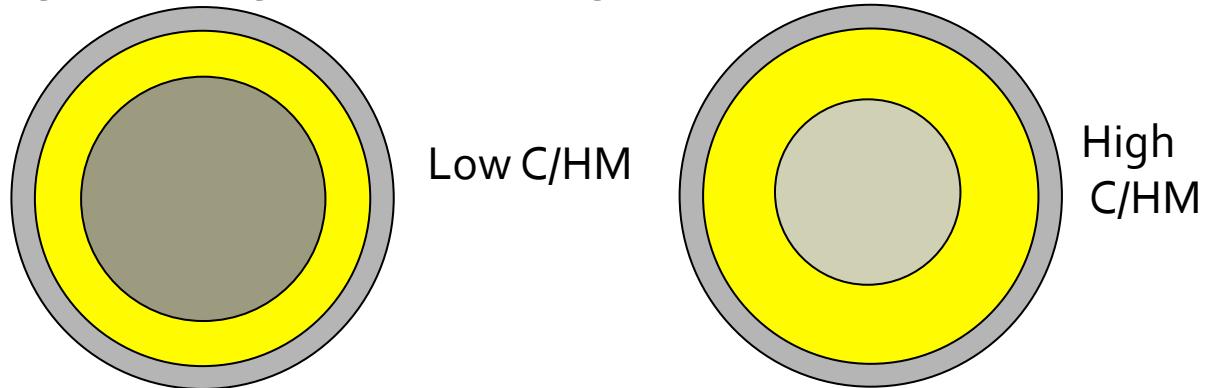
TRISO Scale



# Parametric Design Studies of the FHTR

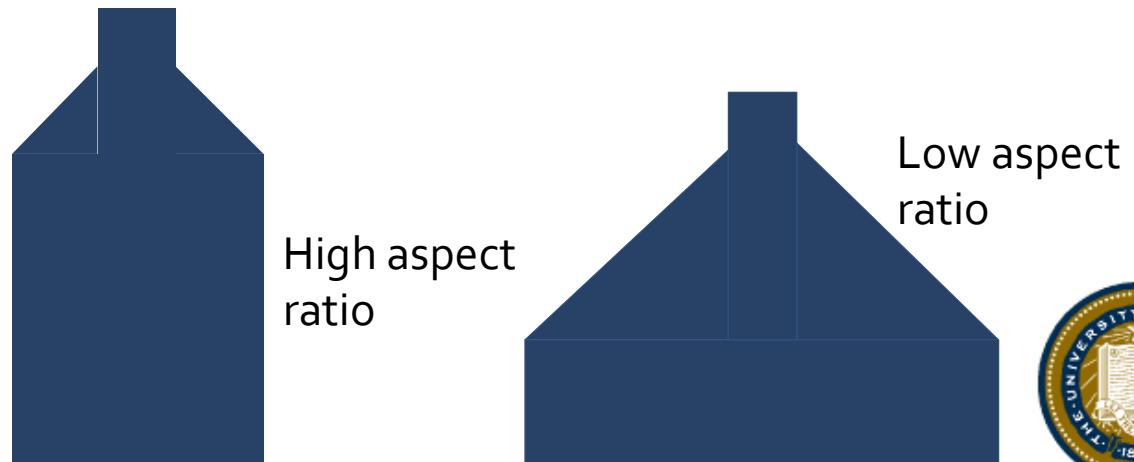
- Fuel Design

- Changing the fuel design with higher HM loadings theoretically should harden the spectrum



- Core Arrangement

- Create cores with high aspect ratios (increases leakage) for enhanced peripheral reactivity control, but also softens neutron energy spectrum.



# MCNP5 Model of the FHTR Core

- TRISO kernels modeled explicitly
- Wall effects on packing fraction

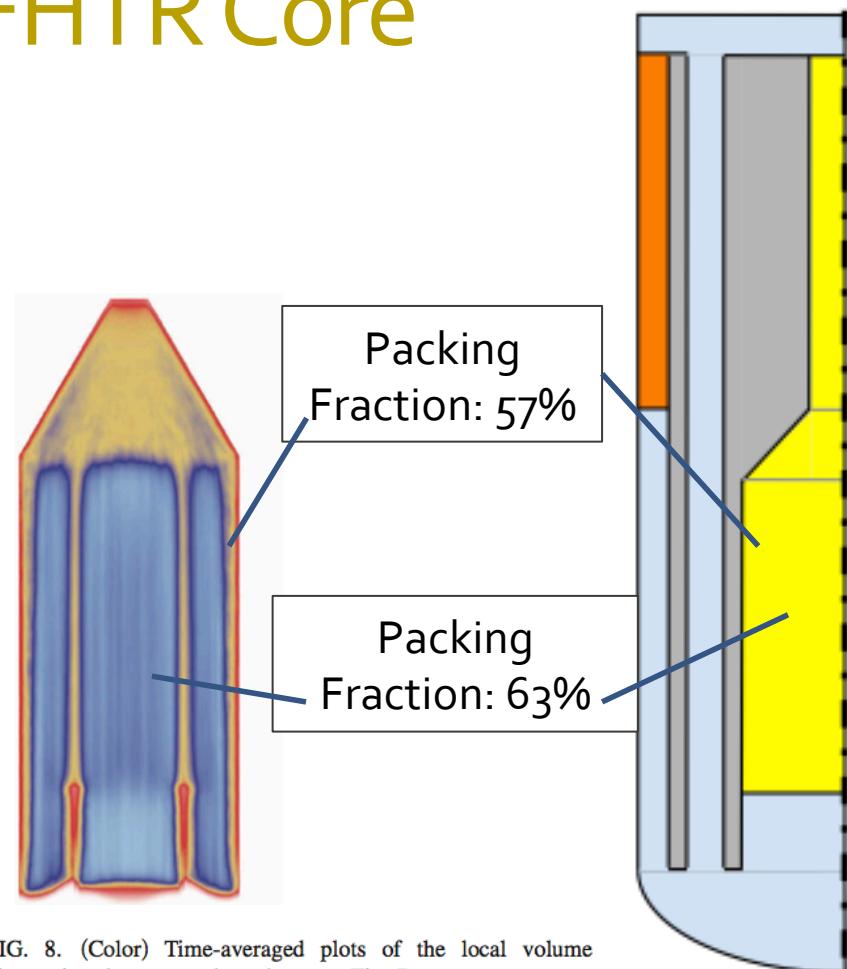
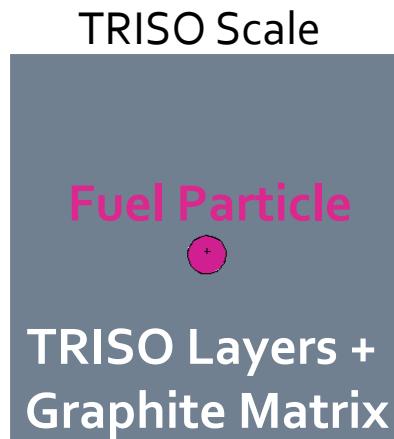
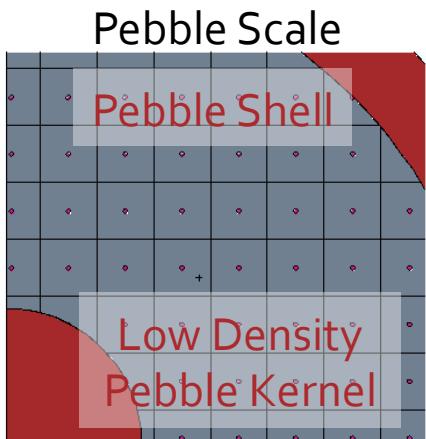
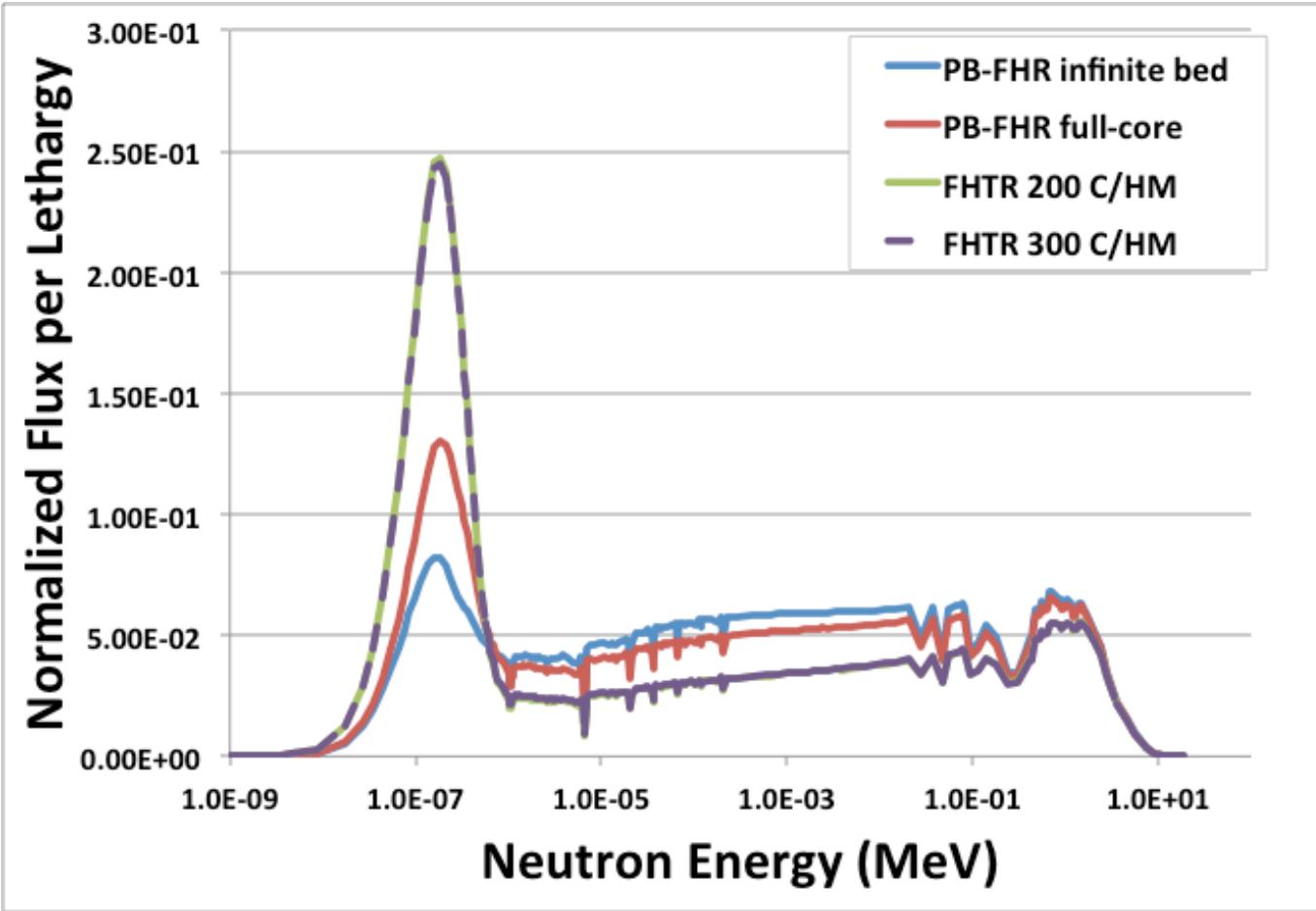


FIG. 8. (Color) Time-averaged plots of the local volume fraction, using the same color scheme as Fig. 7.



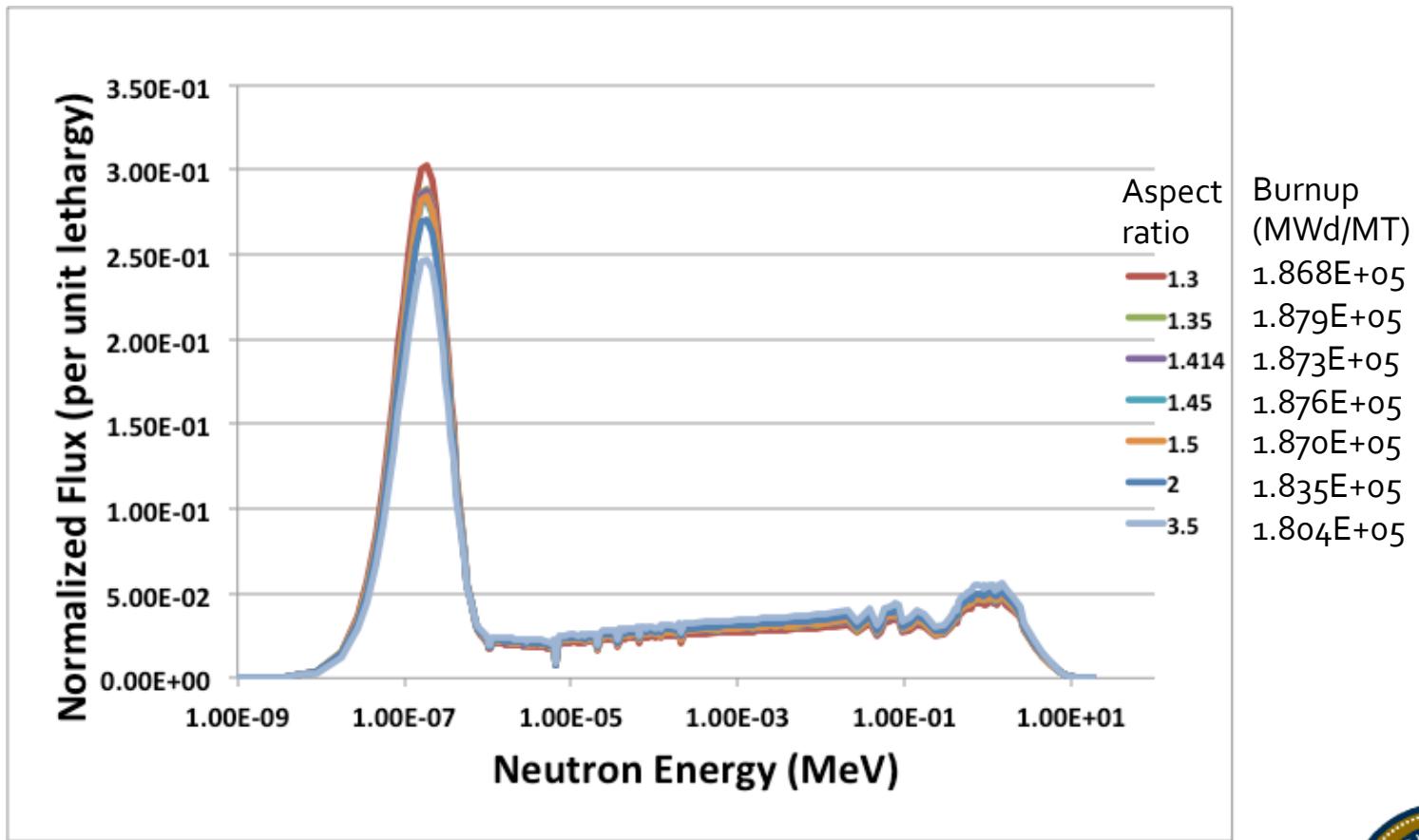
# Effects of Fuel Loading on Neutron Energy Spectrum



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# Effects of Aspect Ratio on Neutron Energy Spectrum



## FHTR Core Parameters (C/HM 200, aspectratio 3.5)

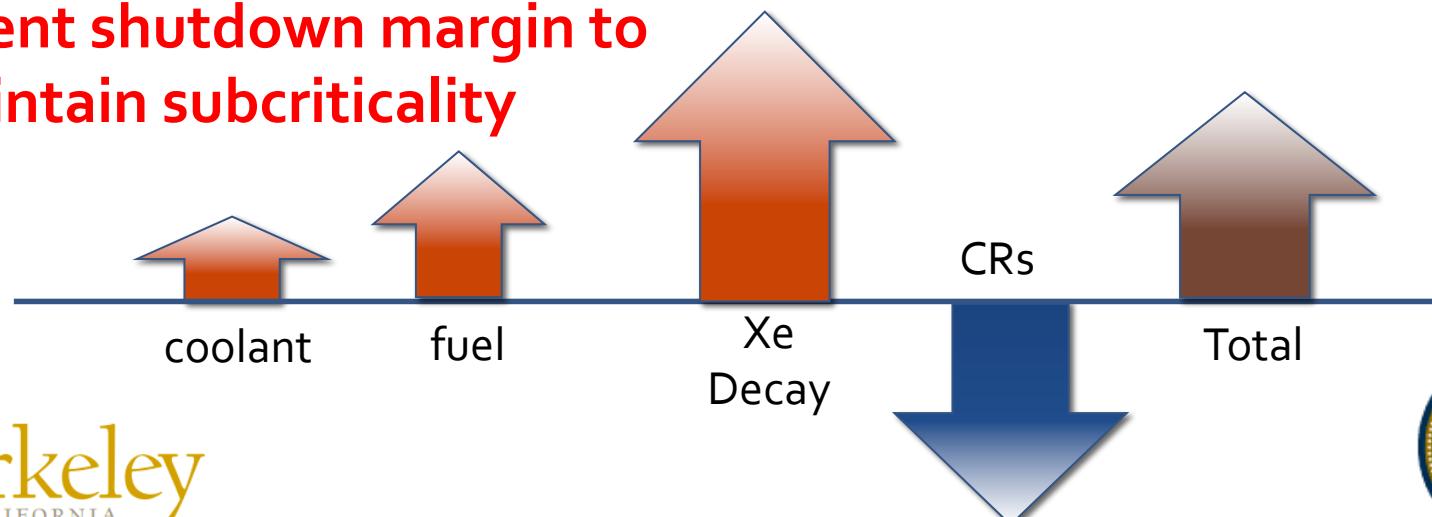
Core Radius (cm)	43.7
Core Total Height (cm)	181.6
Converging Region Height (cm)	28.7
Cylindrical Region Height (cm)	152.9
Reflector Thickness (radial) (cm)	31.2
Reflector Total Height (cm)	375.8
Components beyond Reflectors	
Reactor Pressure Vessel Thickness	0.3
Coolant in Downcomer Thickness	4.8
Core Barrel Thickness	0.3
Coolant Temperature (K)	923.2
Graphite Matrix Temperature (K)	1023.1
Pebble Graphite Temperature (K)	977
Fuel Temperature	997.2
Li-6 concentration	50 ppm
Core Power	20 MWth
Peak Pebble Power	-----
Average Pebble Power	-----



# Best Case Design Summary

FHTTR Core Parameters	
Coolant Reactivity Coefficient (pcm/K)	-1.47 ± .3
Coolant Reactivity Insertion to freezing point of FLIBE (pcm)	+279 ± 3
Fuel Reactivity Coefficient (pcm/K)	-1.56 ± .3
Fuel Reactivity Insertion to freezing point of FLIBE (pcm)	+412 ± 9
Xe decay reactivity insertion (pcm)	+2272 ± 20
Reactivity Insertion from Peripheral Control Rods (pcm)	-1430 ± 15
Total addition to reactivity	+1.540 ± 30

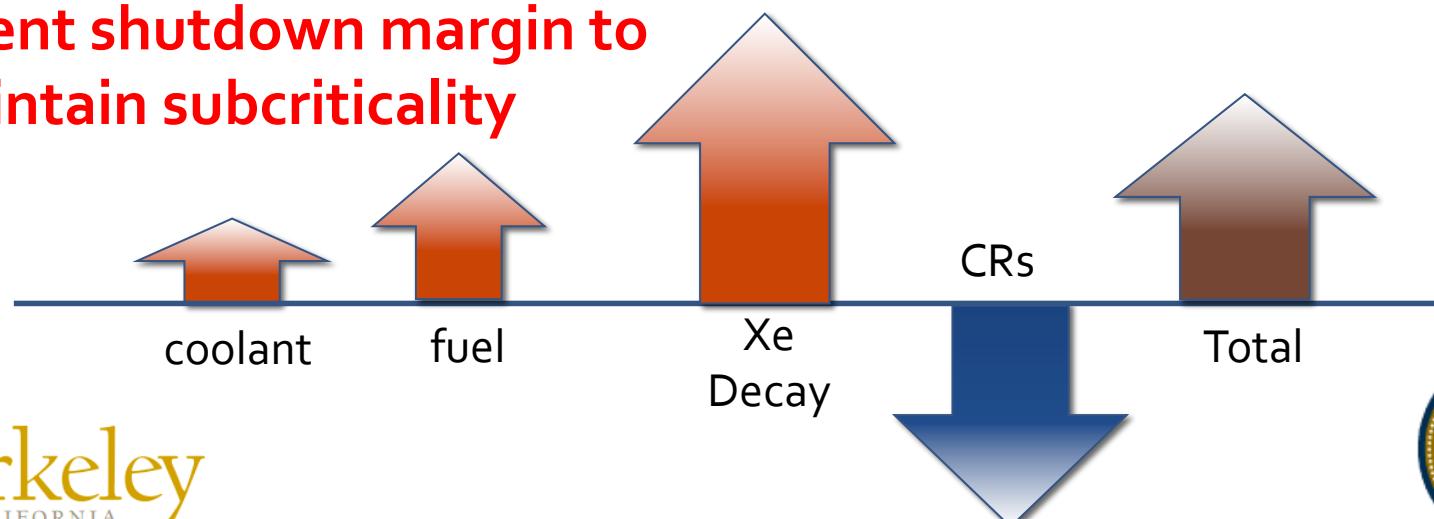
**Insufficient shutdown margin to maintain subcriticality**



# Best Case Design Comparison

	FHTR Core	PB-FHR Core
Equilibrium Burnup	180 GWd/MT	216 GWd/MT
Power Level (MWth)	20	900
Coolant Reactivity Coefficient	$-1.47 \pm 0.3$	$-0.49 \pm 0.1$
Fuel Reactivity Coefficient	$-1.56 \pm 0.3$	$-4.5 \pm 0.2$
Graphite Reactivity Coefficient	---	

Insufficient shutdown margin to maintain subcriticality



# Initial Study: Results and Conclusions

- Changing the heavy metal loading in the fuel didn't appear to have significant hardening effect on the neutron energy spectrum
- Including Xe decay post-shutdown, peripheral reactivity control was not sufficient
- Higher leakage cores appeared to have harder spectrums → reflector effects less prominent than previously thought

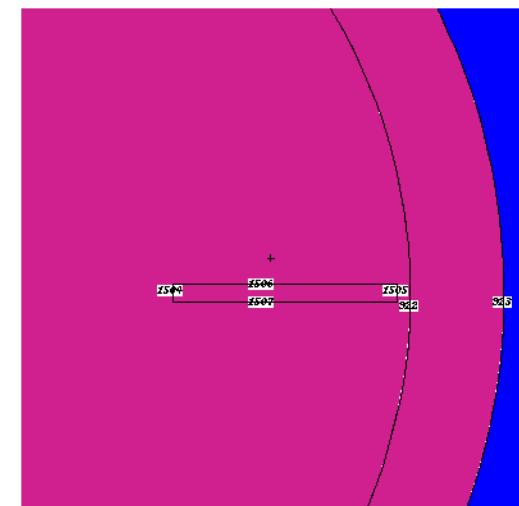
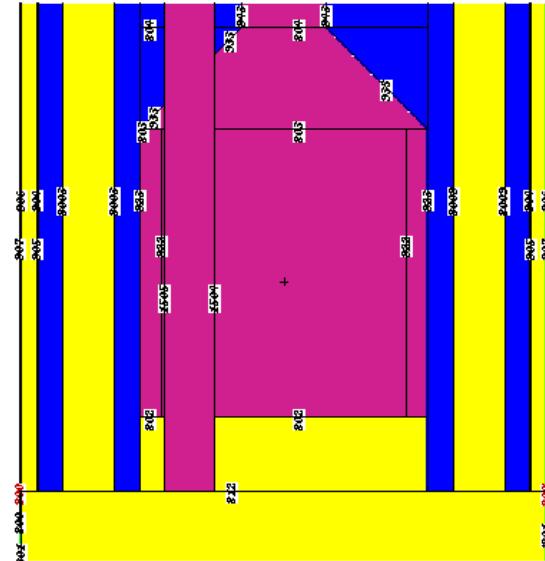
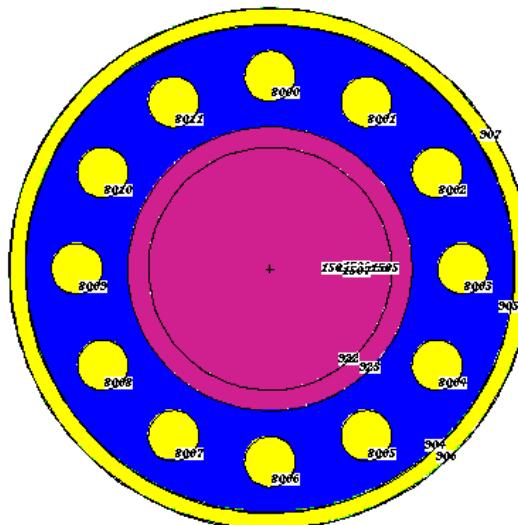
## Going Forward

- Reactivity control changes → control blades
- Investigate much lower C/HM pebble loadings
- Investigate effects of burnup on spectrum evolution

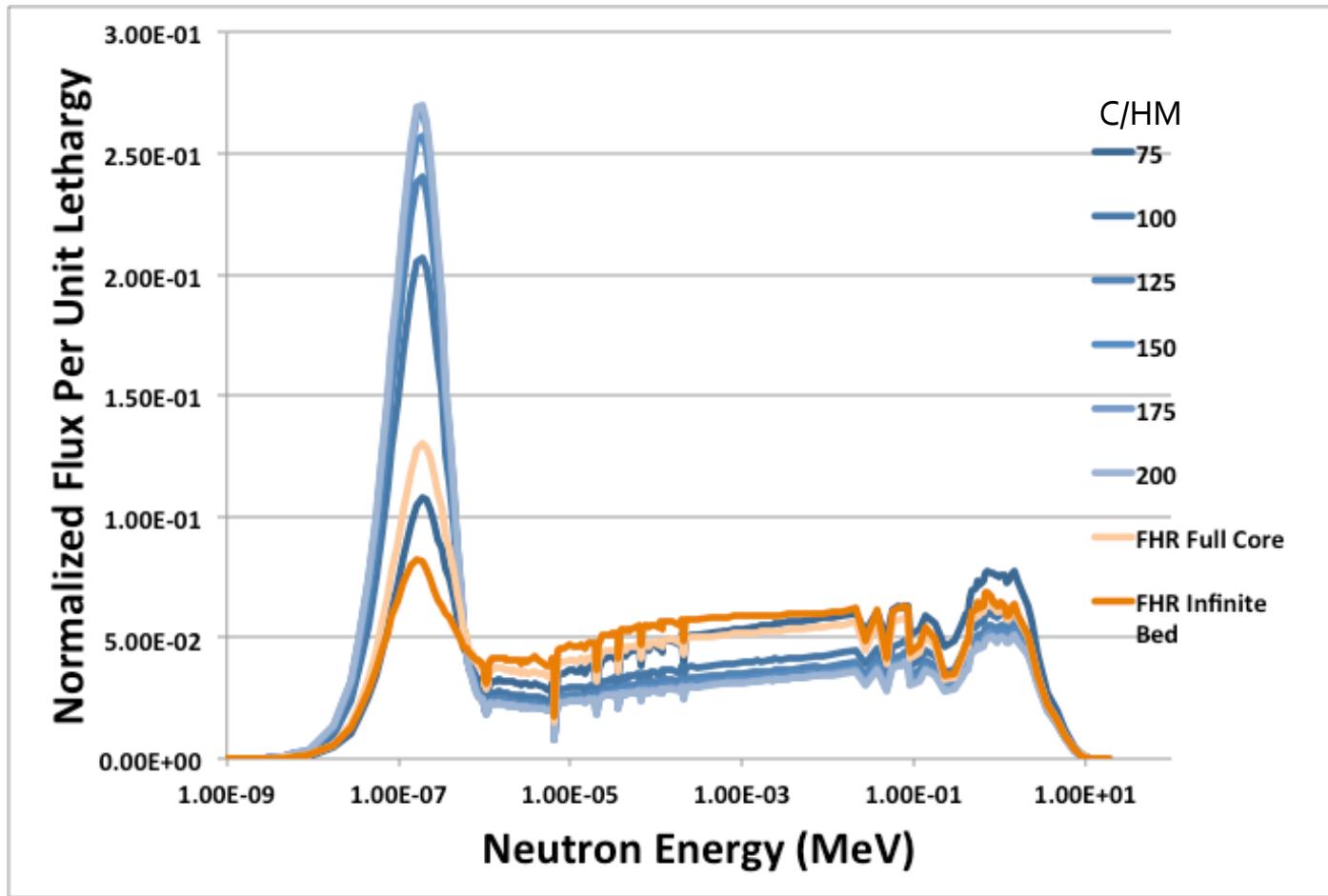


# Control blade design

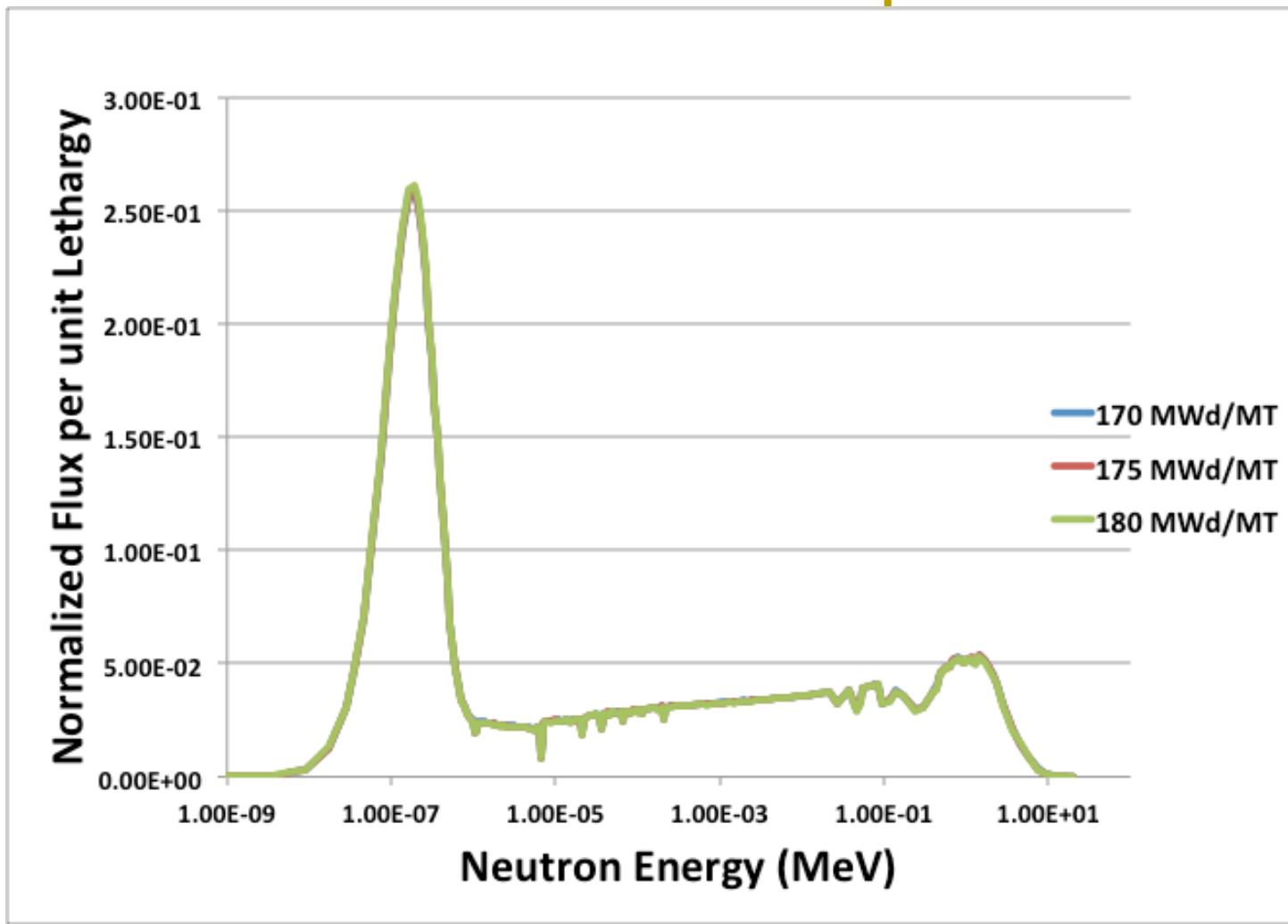
- Control blades inserted directly into the pebble bed
  - Free pebble bed aids in control blade insertion with minimal resistance
  - Experimental work in progress
- Packed Boron Carbide



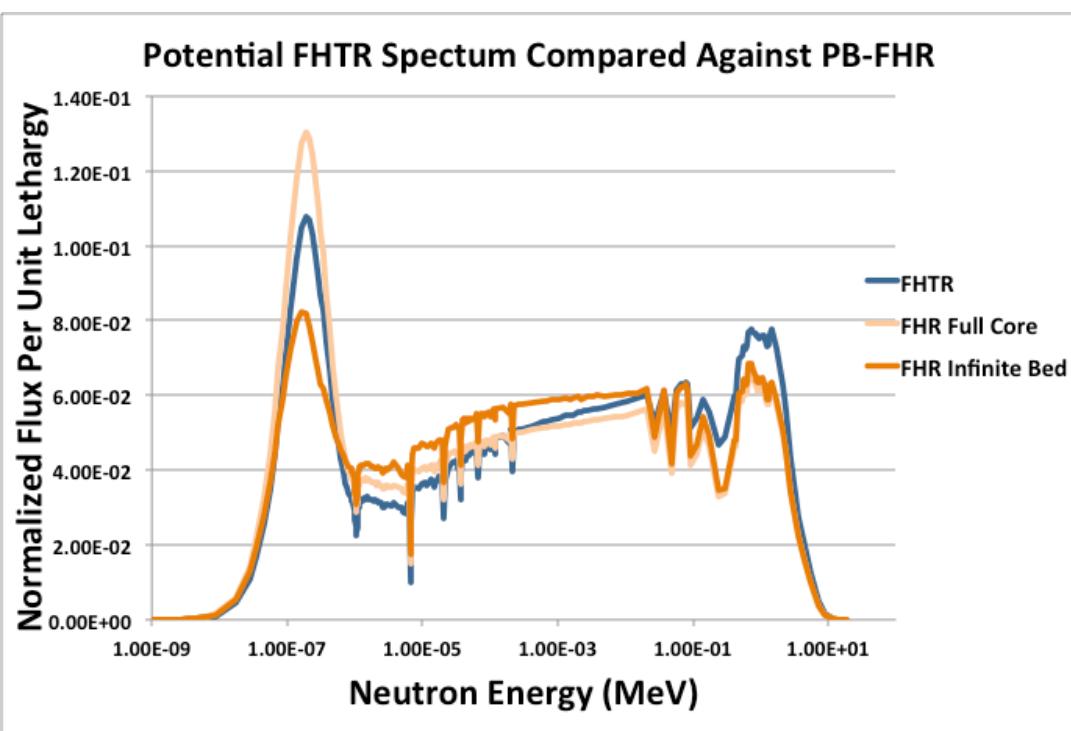
# Spectrum Comparison of FHTRs with changes in C/HM



# Flux Evolution with Burnup



# Design Summary: Potential FHTTR Core (C/HM 75)



FHTTR Core Parameters	
Coolant Reactivity Coefficient (pcm/K)	-3.83 ± .3
Coolant Reactivity Insertion fible freezing (pcm)	665 ± 7
Fuel Reactivity Coefficient (pcm/K)	-3.29 ± .3
Fuel Reactivity insertion to Flibe freezing (pcm)	948 ± 9
Xe decay reactivity insertion (pcm)	+1585 ± 20
Reactivity Insertion from Control Blades (pcm)	-5070 ± 15
Total addition to reactivity	-1872 ± 30

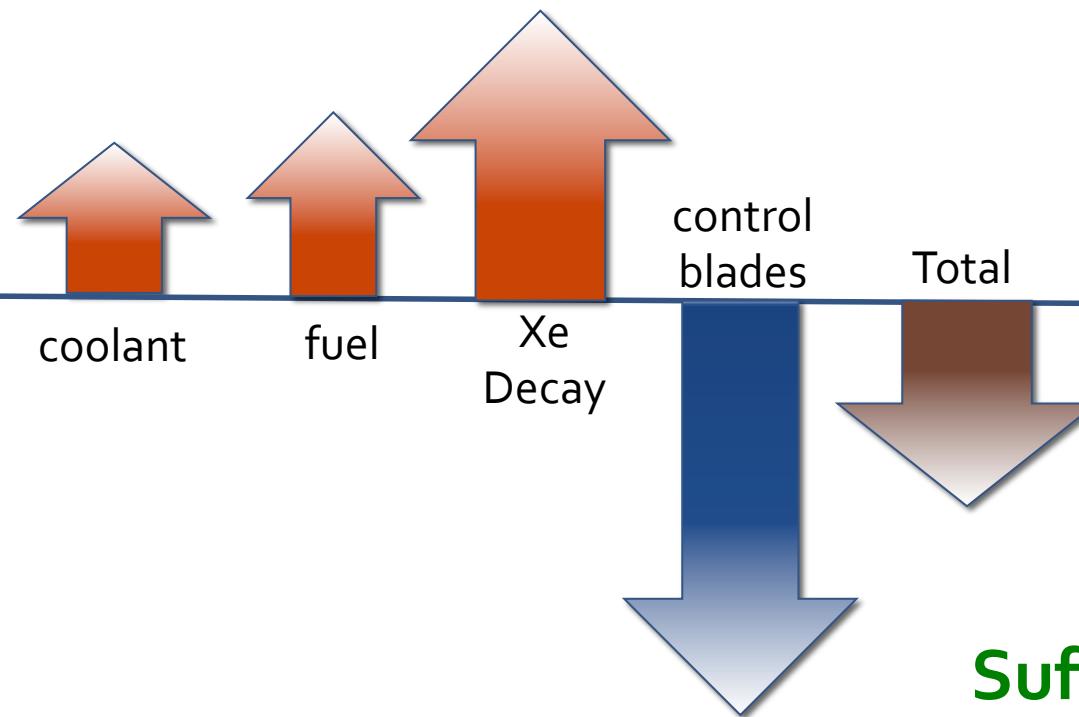


# Design Summary: Potential FHTR Core (C/HM 75)

	FHTR Core	PB-FHR Core
Equilibrium Burnup	180 GWd/MT	216 GWd/MT
Power Level (MWth)	20	900
Coolant Reactivity Coefficient	$-3.83 \pm 0.3$	$-0.49 \pm 0.1$
Fuel Reactivity Coefficient	$-3.29 \pm 0.3$	$-4.5 \pm 0.2$
Graphite Reactivity Coefficient	---	----



# Design Summary: Potential FHTR Core (C/HM 75)



FHTR Core Parameters	
Coolant Reactivity Coefficient (pcm/K)	-3.83 ± .3
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Fuel Reactivity insertion to Flibe freezing (pcm)	948 ± 9
Xe decay reactivity insertion (pcm)	+1585 ± 20
Reactivity Insertion from Control Blades (pcm)	-5070 ± 15
Total addition to reactivity	-1872 ± 30

**Sufficient shutdown  
worth → subcriticality  
maintained**



## FHTR Core Parameters (C/HM 75, aspectratio 2.0)

Core Radius (cm)	51.5
Core Total Height (cm)	139.6
Converging Region Height (cm)	36.5
Cylindrical Region Height (cm)	103.1
Reflector Thickness (radial) (cm)	36.8
Reflector Total Height (cm)	375.8
Components beyond Reflectors	
Reactor Pressure Vessel Thickness	0.3
Coolant in Downcomer Thickness	4.8
Core Barrel Thickness	0.3
Coolant Temperature (K)	923.2
Graphite Matrix Temperature (K)	1023.1
Pebble Graphite Temperature (K)	1012.1
Fuel Temperature	1002.1
Li-6 concentration	50 ppm
Core Power	20 MWth
Peak Pebble Power	-----
Average Pebble Power	-----



# Conclusions

- A FHTR with similar neutronics to the FHR can be designed with larger heavy metal loadings in the fuel.
  - Reactivity control blades sufficient for control + xenon decay
  - Many cores have negative coolant and fuel reactivity coefficients
  - Not all of the effects that affect the changes in spectra have been explored
  - Complete shutdown worth analysis including flibe solification
- Startup core configurations for feasible designs must also be explored
  - Beginning of life criticality
  - Beginning of life safety



# Acknowledgements

- Tommy Cisneros
- Professors Ehud Greenspan and Per Peterson
- Mike Laufer



# References

- [1] 1. UC BERKELEY, "Preliminary Fluoride Salt-Cooled High Temperature Reactor Phenomena Identification and Ranking," UCB-TH-12-002, UC Berkeley (2012).
- [2] A. CISNEROS, et. al, "Pebble Fuel Design for PB-FHR," *Proc. ICAPP 2012*, Chicago, Illinois, June 24–28, 2012, American Nuclear Society (2012).
- [3] A. CISNEROS, E. GREENSPAN, and P. F. PETERSON, "Pebble Bed Reactor Depletion Analysis with Multiple Fuel Types," *Trans. Am. Nucl. Soc.*, (2011).
- [4] C. H. RYCROFT, G. S. GREST, J. W. LANDRY, and M. Z. BAZANT "Analysis of Granular Flow in a Pebble-Bed Nuclear Reactor," *Physical Review E*, 74, 2, 021396 (2004).



# Core characteristics with changes in C/HM

C/HM	Burnup (MWd/MT)	Coolant Reactivity Coeff (pcm/K)	Fuel Reactivity Coeff (pcm/K)
75	1.790E+05	-3.83E+00	-3.29E+00
100	2.068E+05	-1.90E+00	-2.10E+00
125	2.01E+05	-1.25E+00	-1.80E+00
150	1.96E+05	-8.30E-01	-1.69E+00
175	1.90E+05	-6.15E-01	-1.13E+00
200	1.859E+05	-6.22E-01	-1.41E+00
250	1.775E+05	-3.27E-01	-1.35E+00



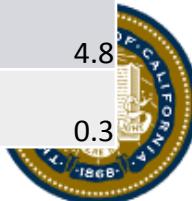
# Core Temperatures (K) with changes in C/HM

Core Region	75	100	125	150	175	200	250	300
Fuel Temp	1002.1	996	994.8	994.9	995.9	997.2	1000.9	1006.9
Graphite Matrix	1023.1	1023.1	1023.1	1023.1	1023.1	1023.1	1023.1	1023.1
Pebble Graphite	1012.1	994.6	987.6	982.8	979.3	977	973.7	973.1
Coolant Temp	923.2	923.2	923.2	923.2	923.2	923.2	923.2	923.2
Core Barrel	873.1	873.1	873.1	873.1	873.1	873.1	873.1	873.1
Coolant in Downcomer	873.1	873.1	873.1	873.1	873.1	873.1	873.1	873.1
RPV	873.1	873.1	873.1	873.1	873.1	873.1	873.1	873.1



# Core Measurements (in cm) with changes in aspect ratio

Core Region	1.3	1.35	1.414	1.5	2.0	2.5	3.0	3.5
Total Height	118.5	120	122	124.6	139.6	154.1	168	181.6
Main Height	75.5	77.6	80.3	83.8	103.1	120.8	137.3	152.9
Contracting ht	43	42.5	41.8	40.9	36.5	33.3	30.8	28.7
Active Radius	58	57.5	56.8	55.9	51.5	48.3	45.8	43.7
Aspect Ratio	1.3	1.4	1.4	1.5	2	2.5	3	3.5
Reflector Thickness	41.5	41.1	40.6	39.9	36.8	34.5	32.7	31.2
Reflector Height	296.7	298.7	301.2	304.5	323.4	341.6	359	375.8
Core Barrel Thickness	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Downcomer Thickness	6.3	6.2	6.2	6.1	5.6	5.3	5	4.8
RPV Thickness	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3



# Checklist

- Estimate reactivity effect due to graphite temperature change
- Dimensions of All cores evaluated
  - Diameter and height, thickness of graphite reflectors